

# **FY2010 Annual Report of "Data Assimilation and Predictability Studies for Improving Tropical Cyclone Intensity Forecasts"**

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## **LONG-TERM GOALS**

This project aims to understand and improve the forecast of Tropical Cyclone (TC) lifecycle evolution and intensity, focusing on both large-scale environment and mesoscale phenomena in the TC system, which are major components responsible for intensity change. Two major challenges in TC intensity forecasting are the general lack of observations in the vicinity of TCs and the adaptive representation of the forecast error covariance. This project attempts to address both challenges for improving TC intensity forecasting.

## **OBJECTIVES**

Intensive T-PARC (THORPEX<sup>1</sup> Pacific Asian Regional Campaign) observations and other available observations will be assimilated with the LETKF (Local Ensemble Transform Kalman Filter) into the CFES (Coupled ocean-atmosphere general circulation model For the Earth Simulator) and the WRF (Weather Research and Forecasting) mesoscale model to study 1) the characteristics and role of coupled ocean-atmosphere covariance, 2) the impact of each observation assessed by an efficient ensemble sensitivity analysis method, 3) a better way to assimilate observations in the vicinity of the TC center and potential usefulness of Lagrangian data assimilation (LaDA), 4) several new data assimilation techniques to improve the performance of LETKF, and 5) the predictability of TC intensity due to the uncertainty of initial conditions.

## **APPROACH AND WORK PLAN**

This project has two major components with the CFES and WRF models. LETKF experiments with the CFES model is performed on the Earth Simulator (ES) supercomputer system. First, Co-I Enomoto (Earth Simulator Center) performs data assimilation experiments with the atmospheric part of CFES

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<sup>1</sup> THORPEX (The Observing System Research and Predictability Experiment) is an international research and development program of the World Meteorological Organization (WMO).

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(AFES: Atmospheric general circulation model For the Earth Simulator). With the AFES-LETKF system, the impact of LaDA of T-PARC's driftsonde observations is investigated by PI Miyoshi and Co-PI Ide. Miyoshi, Enomoto, and Co-I Komori develop the LETKF system with CFES and perform data assimilation and ensemble prediction experiments. Miyoshi and Co-I Yang study the characteristics of coupled ocean-atmosphere covariance and its impact on TC forecasts.

Experiments with the WRF model are performed on the newly acquired cluster server through this project support. First, the WRF-LETKF system is developed by Miyoshi and Researcher Kunii at the University of Maryland (UMD). Data assimilation and ensemble prediction experiments are performed to study the impacts of the T-PARC observations on TC intensity forecasts and predictability. Higher resolution experiments are performed to simulate mesoscale phenomena in the TC system.

Ensemble sensitivity analysis of observations and new data assimilation techniques to improve the LETKF are common to both components. Miyoshi and Co-PI Kalnay study sensitivity analyses of observations. Miyoshi and Co-I Li work on theoretical developments of adaptive estimation methods of covariance inflation and observation errors. Miyoshi and Co-PI Bishop study adaptive localization methods. Miyoshi and Yang apply the running-in-place method to find its impact on TC intensity forecasts.

Our work plan for the upcoming year includes several system developments and scientific explorations. We will start developing the CFES-LETKF system, higher-resolution WRF-LETKF system, and ensemble sensitivity analysis system. In addition to scientific explorations relevant to these system developments, LaDA of driftsonde observations and improvement to the newly-developed adaptive inflation method will be explored.

## **WORK COMPLETED**

In the component of global data assimilation, AFES-LETKF data assimilation experiments were performed with the Earth Simulator with real observations in 2008. In the component of mesoscale data assimilation, the WRF-LETKF system has been developed and assessed with T-PARC observations in the case of Typhoon Sinlaku (2008) (1 paper submitted, 1 conference presentation). In addition, we have made three fundamental achievements: 1) a new adaptive inflation method has been developed for improving the LETKF (1 paper accepted, 5 conference presentations with 1 invited), 2) the impact of observation error correlations on data assimilation was examined (1 paper submitted, 3 conference presentations with 1 invited), and 3) importance of the initial conditions in TC forecasts using the Japanese operational global system has been published (1 paper published).

## **RESULTS**

The most significant achievement in FY2010 is the new development of the adaptive inflation method with the LETKF. This fundamental improvement has the broad impact on any applications of the LETKF. Among many applications, our experiments with the newly developed WRF-LETKF system focusing on TC forecasts have been greatly benefited. In ensemble Kalman filters, the underestimation of forecast error variance due to limited ensemble size and other sources of imperfection is commonly treated by empirical covariance inflation. In order to avoid manual optimization of inflation parameters, previous studies proposed adaptive inflation approaches. Anderson (2007; 2009) applied Bayesian estimation theory to the probability density function of inflation parameters. Alternatively, Li et al. (2009, "LKM09") used the innovation statistics of Desroziers et al. (2005) and applied a Kalman filter

analysis update to the inflation parameters based on the Gaussian assumption. In the new method, LKM09's Gaussian approach is advanced to include the variance of the estimated inflation as derived from the central limit theorem. It is shown that the Gaussian approach is an accurate approximation of Anderson's general Bayesian approach. The new method is an advanced implementation of the Gaussian approach with the LETKF, where the adaptive inflation parameters are computed simultaneously with the ensemble transform matrix at each grid point. This has brought significant improvement to WRF-LETKF in the case of Typhoon Sinlaku (2008) with T-PARC observations. Figure 1 shows the adaptive inflation field at the 15th model level ( $\sim 500$  hPa) and the observing network. Contours indicate the inflation factors multiplied to the background error covariance (e.g., 1.0 is no inflation, 1.1 is 10 % covariance inflation). Larger inflation values are estimated in densely observed areas; occasionally it exceeds 100 % inflation, which helps increase the ensemble spread to a more appropriate level. By contrast, the non-adaptive fixed inflation has a single value, chosen to be 1.2 after manual tuning, everywhere on the map, and results in too small (large) ensemble spread over the densely (sparsely) observed areas. As a result, adaptive inflation improved the forecast accuracy and its error variance estimate significantly. Figure 2 shows 6-h forecast verifications relative to radiosonde observations for (a) zonal wind component ( $\text{m s}^{-1}$ ) and (b) temperature (K), averaged over 14 days from 1200 UTC 5 September 2008 to 1200 UTC 19 September 2008. Solid and dashed lines correspond to adaptive and fixed inflation, respectively, and thick and thin lines indicate root mean square errors (RMSE) and biases, respectively. With adaptive inflation, both bias and RMSE are improved significantly and consistently.

Another notable achievement was obtained from the global ensemble data assimilation with the Earth Simulator. As Enomoto et al. (2010) indicated, the analysis ensemble spread from AFES-LETKF tends to show rapid increase just before atmospheric disturbances occur. This was true to a typhoon as shown in Fig. 3. Large ensemble spread of zonal wind component ( $\text{m s}^{-1}$ , color shades) on July 17, 2005 appeared just before the typhoon generation. Predictability studies using the LETKF ensemble perturbations are main foci of this project.

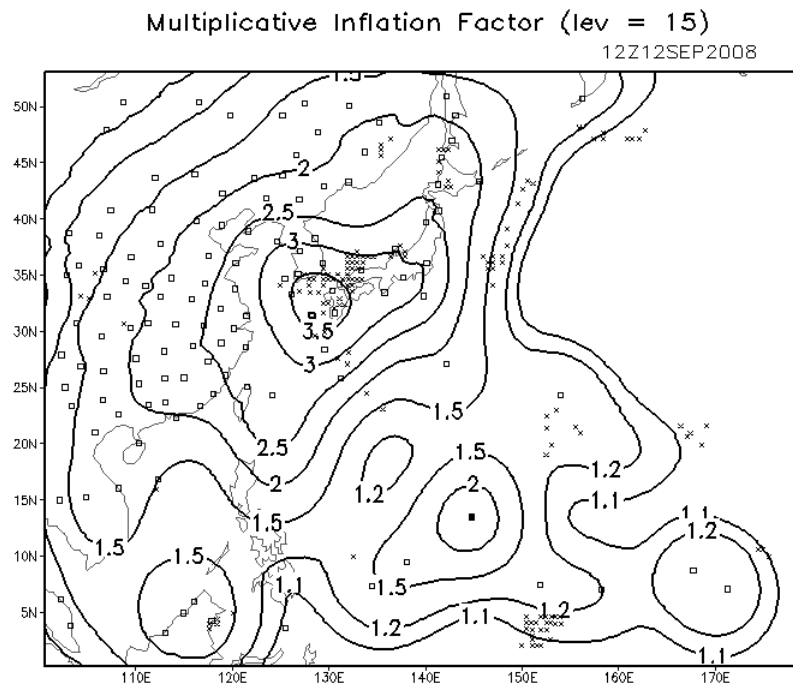


Fig. 1

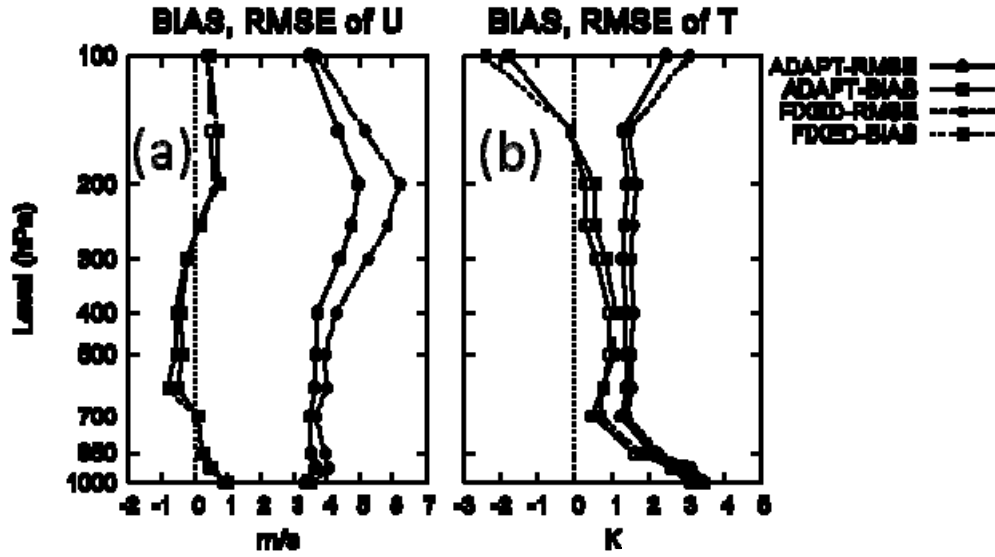


Fig. 2

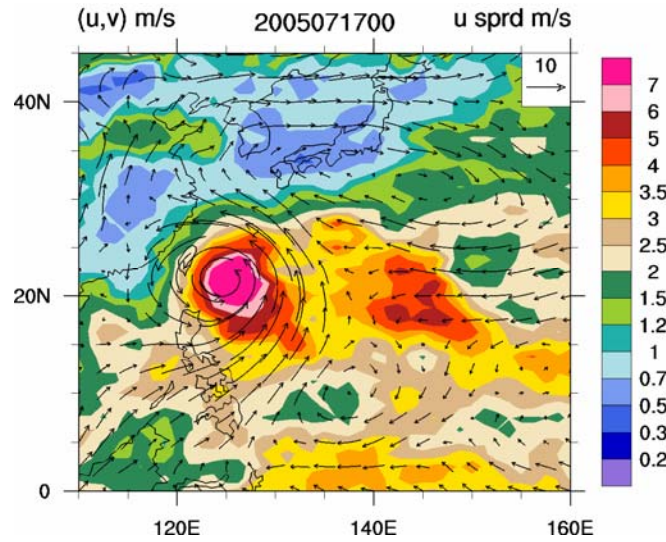


Fig. 3

The successful development of the WRF-LETKF system is an essential first step to the mesoscale studies in the upcoming years. We have developed the entire system by taking advantage of the existing systems as much as possible, such as the WRF model system developed by NCAR (National Center for Atmospheric Research), and the LETKF and related software developed at UMD. A particular attention was made to design the input/output interface of the LETKF to be simple, so that it can be adapted relatively easily to other mesoscale NWP models. Figure 4 shows horizontal maps of 6-h accumulated precipitation (mm, shades), mean-sea-level pressure (hPa, contours) and wind vectors ( $\text{m s}^{-1}$ ) at 850 hPa on 1200 UTC 12 September 2008 for (a) NCEP/NCAR reanalysis, (b) the case without assimilating observations, (c) the case with assimilating observations. The main focus is Typhoon Sinlaku (2008) located just east of Taiwan before landfall. No TC is generated without observations; the prescribed lateral boundary conditions and sea surface temperature are irrelevant. Assimilating real observations including T-PARC observations near the Typhoon center successfully reproduced the intense Typhoon Sinlaku at the right location.

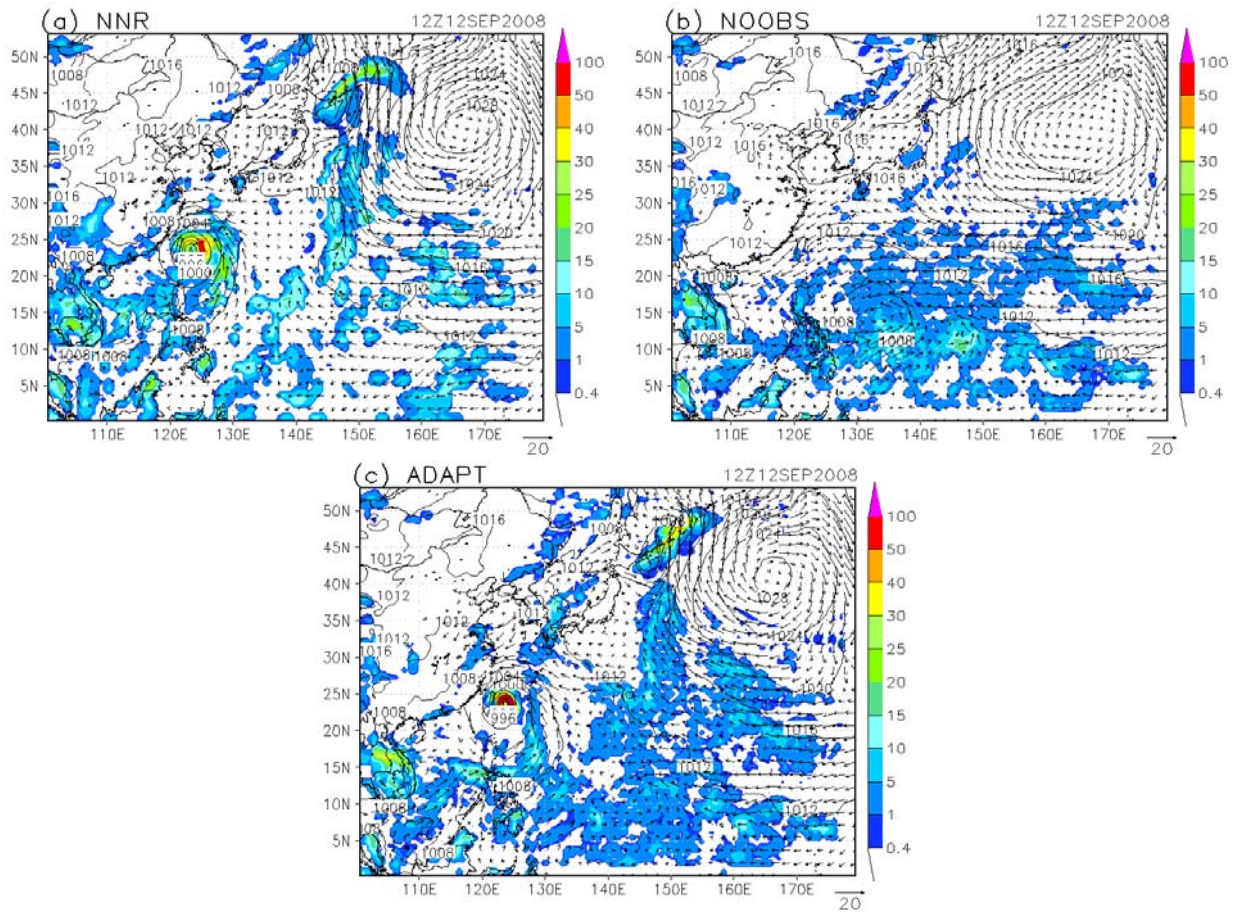


Fig. 4

A theoretical study on the impact of observation error correlations was also conducted. Usually in data assimilation, the observation error covariance matrix  $\mathbf{R}$  is assumed to be diagonal for simplicity and computational efficiency, although there are studies indicating that several types of satellite observations contain significantly correlated errors. We investigated the impact of the off-diagonal terms of  $\mathbf{R}$  in data assimilation. The adaptive estimation method of LKM09, which allows online estimation of the observation error variance using innovation statistics, was extended to include off-diagonal terms of  $\mathbf{R}$ . The extended method performed well with the 40-variable Lorenz model in estimating non-diagonal observation error covariances. Interestingly, the analysis accuracy was improved when the observation errors were correlated, but only if the observation error correlations were explicitly considered in data assimilation. Further theoretical considerations related the impact of observing systems (characterized by both  $\mathbf{R}$  and an observation operator  $\mathbf{H}$ ) on analysis accuracy. This analysis points out the importance of distinguishing between observation error correlations (i.e., non-diagonal  $\mathbf{R}$ ) and correlated observations (i.e., non-orthogonal  $\mathbf{H}$ ). In general, observations with a non-diagonal  $\mathbf{R}$  carry more information, whereas observations with a non-orthogonal  $\mathbf{H}$  carry less information, so that it is essential to account for both  $\mathbf{R}$  and  $\mathbf{H}$ : positively (negatively) correlated observations with negatively (positively) correlated errors carry more information and result in a more accurate analysis.

Finally, we published the findings from the operational NWP systems at the Japan Meteorological Agency (JMA), which indicated that the typhoon track forecasts made by the control member of the



ensemble prediction system (EPS) tended to be worse than those made by the high-resolution global NWP. The control forecast of the EPS with horizontal triangular truncation at 319 wavenumbers and 60 vertical levels (T319/L60 resolution) was initialized by eliminating the higher-wavenumber components of the global analysis at T959/L60 resolution. When the data assimilation cycle was performed at the lower T319/L60 resolution, the forecast gave typhoon track forecasts closer to the high-resolution global NWP. Therefore, it stands to reason that the resolution transform of the initial condition must be responsible for the degradation of the typhoon track forecasts at least to considerable extent. To improve the low-resolution forecast, two approaches were tested: 1) applying a smoother spectral truncation for the resolution transform and 2) performing noncycled lower-resolution data assimilation during preprocessing. Results from the single case study of Typhoon Nuri (2008) indicated almost no impact from the former approach, but a significant positive impact when using the latter approach. The results illuminate the importance of considering a model's resolving capability during data assimilation. Namely, if the initial conditions contain features caused by unresolved scales, degraded forecasts may result.

## **IMPACT AND APPLICATIONS**

### **National Security, Economic Development, and Quality of Life**

The goal of this project is to improve the LETKF and the prediction of TCs, with particular focus on the TC lifecycle evolution and intensity. Better prediction of TCs with quantitative measure of its uncertainty has the significant impact on National Security, Economic Development, and Quality of Life, since military operations, economic activities, and people's life are affected by extreme weather.

### **Science Education and Communication**

Data assimilation provides a bridge between the nature and computer simulations, and the LETKF is a general and practical approach to data assimilation. This project aims to improve the LETKF, which may have potential impact on Science Education, particularly on emerging and rapidly expanding applied mathematics and scientific computing fields.

## **TRANSITIONS**

### **National Security, Economic Development, and Quality of Life**

The Japan Meteorological Agency (JMA) and INPE/CPTEC (Brazilian Institute for Space Research and Brazilian Weather Service) are developing the LETKF for possible future operations, and the findings from this project have been directly transferred to their preoperational systems. This is an important path of transitioning the achievements of this project to the operational NWP, which in turn benefits to National Security, Economic Development, and Quality of Life. We would like to seek similar paths to the US institutions.

### **Science Education and Communication**

The LETKF system is widely available through the internet (<http://code.google.com/p/miyoshi/>), which has been used in Science Education for students and researchers at UMD and many other places worldwide, including the JMA, Tohoku University (Japan), University of Buenos Aires (Argentina), and INPE/CPTEC (Brazil). In addition, the fundamental improvements as a result of this project have been applied in many studies at the UMD and other places worldwide.

## RELATED PROJECTS

There are several related and mutually beneficial projects.

1. The Tropical Cyclone Structure-2008 (TCS-08) program is sponsored primarily by the Office of Naval Research (ONR) with funding also from the National Science Foundation for shared aircraft resources. The objectives of TCS-08 address mechanisms and predictability of tropical cyclone formation, intensification, and structure change. The observation data are a key part of T-PARC and are assimilated in our NOPP project.
2. The Impacts of Typhoons on the Ocean in the Pacific (ITOP) program is also sponsored by ONR and is a multi-national field campaign that aims to study the ocean response to typhoons in the western Pacific Ocean. Our NOPP project is closely related and has mutual benefit. The new techniques pioneered with T-PARC/TCS-08 observations can be independently tested with the ITOP/TCS-10 observations.
3. The Japan Meteorological Agency (JMA) and INPE/CPTEC are developing the LETKF for possible future operations, and our achievements to improve the LETKF are beneficial to their development, and their results help us to know how our achievements apply to the real-world operational NWP.
4. Steve Penny (UMD graduate student) is completing his doctoral dissertation based on the LETKF coupled with the MOM2 global ocean model to perform advanced ocean data assimilation. His current results indicate a very large improvement when compared with SODA (Simple Ocean Data Assimilation), a reanalysis based on a standard state-of-the-art 3D-Var data assimilation system. The adaptive inflation scheme improved his MOM2-LETKF results significantly.
5. Steve Greybush (UMD graduate student) is completing his doctoral dissertation this Spring has also benefited from the adaptive inflation in his LETKF application to Mars atmosphere, with very encouraging results.
6. Ji-Sun Kang (UMD postdoctoral researcher) has benefited from adaptive inflation in the estimation of the surface fluxes of carbon from atmospheric CO<sub>2</sub> data assimilation. Her experiments led to the concept of "variable localization" that in turn improves the LETKF.
7. Luciano Pezzi (INPE/CPTEC, Brazil) uses the LETKF for regional ocean data assimilation and had very encouraging results with adaptive inflation.
8. Prof. Shu-Chih Yang (Taiwan Central University) is testing her new "outer loop" approach for TC data assimilation with encouraging results. She is a Co-I of our NOPP project, and this is clearly mutually beneficial.
9. Prof. Hong Li (Shanghai Typhoon Institute, China) has applied the ensemble sensitivity analysis method using the LETKF to a low-resolution global atmospheric model for assessing the impact of different types of simulated observations in ideal experiments. She is a Co-I of our NOPP project, and this is clearly mutually beneficial.
10. Juan Ruiz (University of Buenos Aires, Argentina) uses the LETKF system for model's parameter estimation. His experience with imperfect model experiments had direct benefit to our study on adaptive inflation in designing ideal experiments.

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- Miyoshi, T., E. Kalnay, and H. Li, 2010: Estimating and applying observation error correlations. under review.
- Miyoshi, T. and M. Kunii, 2010: The local ensemble transform Kalman filter with the Weather Research and Forecasting model: experiments with real observations. under review.

## **OUTREACH MATERIALS**

We developed a webpage on highlighting this project to public:

<http://www.atmos.umd.edu/~miyoshi/nopp/>

The Fortran code and UNIX shell scripts of the LETKF and related software are widely available:

<http://code.google.com/p/miyoshi/>